# TIME-COST RELATIONSHIPS IN CONSTRUCTION

BY
ROBERT D. BAKER



A REPORT PRESENTED TO THE GRADUATE COMMITTEE
OF THE DEPARTMENT OF CIVIL ENGINEERING IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF ENGINEERING

UNIVERSITY OF FLORIDA

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# CHAPTER ONE

## INTRODUCTION

The control of time is one of the basic goals of all parties involved in a construction project. From the initial concept, the owner is interested in the time it takes for the finished project to be delivered. The owner's goal is to shorten the time it takes for each phase of the project--from initial planning through construction execution. Time is money. The economic significance of time is what prompts the owner to use the words "time is of the essence" in a contract. There are many facets of the construction process in which time can be directly controlled by the owner. With other elements, the owner can only exercise indirect control over time--usually with contract clauses and contracting procedures.

The contractor is in the best position to exercise the most direct control over the duration of the construction phase. The network schedule is used by the contractor for project control; however, the duration of the project is usually a condition of the contract between the owner and the contractor. The owner may specify the contract duration based on economics, weather considerations, or some arbitrary reason.

It is not until after signing the contract that the contractor generates a detailed network schedule. After development of the schedule, the contractor may find it necessary to shorten, or "compress" the construction time. The initial schedule's duration may be longer than the time required in the contract and adjustments must be made to satisfy contract provisions. The contractor may want to finish the project early to take advantage of bonus payments, to avoid the winter season, or to free up resources for other projects. In addition, the contractor may fall behind schedule during construction, requiring action to get back on track. In these instances, the contractor needs to determine the project duration at which construction costs are minimized.

The purpose of this report is to examine approaches to reduce the total time spent throughout all phases of the construction process and to present a methodology to establish the project duration that results in the lowest construction costs.

# CHAPTER TWO

## SCHEDULE COMPRESSION TECHNIQUES

Schedule compression can be defined as "the shortening of the required time for accomplishing one or more engineering, procurement, construction, or startup tasks (or a total project), to serve one of three purposes: reducing total design-construct time from that considered normal; accelerating a schedule for owner convenience; and recovering lost time after falling behind schedule" (4:2).

Compression techniques are easiest to apply in the project planning phase, such as when the construction schedule--as initially planned--is longer than the proscribed contract duration. The project manager can compress the schedule before construction is started. Compression becomes more difficult if necessary to get a project back on schedule after it has fallen behind. The project manager is under a great deal of pressure and often does not have the time to apply the most cost effective techniques for compression.

The Construction Industry Institute has cataloged more than 90 compression techniques, grouped into eight different categories: Ideas Applicable to All Phases of a Project, Engineering Phase, Contractual Approach, Scheduling, Materials Management, Construction Work Management, Field Labor Management, and Startup Phase. Some techniques shorten an

activity's schedule time while others prevent needless time losses associated with project activities or management actions. A summary of these techniques follows (4:3-18).

Ideas Applicable to All Phases of a Project

Sound management practices can reduce the project time through all phases, from inception to completion of construction. The management organization must be well defined and staffed efficiently. The organizational structure should clearly establish all reporting, communication, and control lines. Narrative position descriptions that delineate the authority, responsibility, and accountability of each position must be maintained. Organizational clarity can reduce the potential for delays caused by confusion over who is responsible for what, who needs to be informed, and when. Excessive layers of line management should be avoided. Excessive layering usually produces conflicting instructions and unnecessary filtering of information and reviews that add extra time to task accomplishment.

A personnel management system that uses job descriptions, selective recruiting or hiring, performance appraisals, performance incentives, orientation, and training will ensure that the people hired are the most capable for managing and performing the work. Good personnel management practices can avoid delays caused by having the wrong people in the job.

The use of participatory management systems such as Deming's Total Quality Management can help reduce delays by

obtaining workers' ideas for reducing inefficiencies and increasing productivity. Possible techniques include delay surveys, quality circles, work studies, problem solving teams, suggestion programs, and worker discussions. When considering participatory management techniques, it is important to use them within the framework of the organization. Care must be taken to ensure that these techniques do not undermine the decision making authority of managers as specified in the organizational structure.

The idea of "partnering" and "teamwork" should be emphasized throughout the life of the entire project. The owner, engineer, contractor, subcontractor, and key suppliers make up the team. Partnering is the fair sharing of responsibilities and risks among these project contributors. Partnering uses non-adversarial contracting methods that promote openness and trust. The objective is to share project goals among the principles. Teamwork is achieved through the mutual support and cooperation among the players involved in the project. Team building sessions during team organization and before construction will promote mutual understanding of project goals and procedures and establish the problem solving mechanism. Subsequent sessions throughout the course of the project are necessary to deal with new situations. Many barriers to progress on the project can be eliminated by using these ideas.

Management at the project and activity level should try to avoid interruptions of worker concentration that will

reduce productivity. Employees stopping work to visit with other employees, giving revised or additional instructions, deliveries, or noisy activities in adjacent areas are typical interruptions experienced on construction projects. Work should be planned so that instructions and supply or material deliveries take place before work on an activity begins.

Planning cannot be overemphasized. Complete planning is a common ingredient in all successful projects. All work must have the benefit of complete and thorough planning. Long-range planning, short-range planning, individual activity planning, and contingency planning are all extremely important and must not be overlooked. Proactive planning is the objective, not concurrent planning--or "planning as you go." Special attention to environmental, permitting, and community interest matters can avoid serious delays.

Complex work assignments can be broken into smaller, well-defined, short-duration tasks for which milestones can be established to facilitate control. This reduction of task scope makes it easier for engineers, managers, and workers to understand the scope of work and avoid the confusion and delays caused by work assignments that are not clearly understood. This technique, suitable for both engineering and construction tasks, eliminates time lost in analyzing complex tasks before activity accomplishment.

## Engineering Phase

The project design can have an impact on the time associated with procurement and construction. If the design engineer keeps material procurement and construction in mind during the engineering phase, he can develop a design that can save time in these later phases.

The most expeditious and cost effective methods of construction can be promoted if experienced construction personnel have the opportunity to review engineering design concepts before the start of the detailed design procedures. These constructability reviews consider options such as prefabrication, modularization, and other methods. Layout and material selection also may be influenced through these reviews.

Some designs allow components or facilities to serve both a construction function as well as a function in the completed structure. Steel used as forms and a structural member in some concrete structures is an example of this dual-purpose design method. Pipe columns and piers formed with sheet-piling use this dual-purpose concept for steel. The early construction of selected permanent facilities and their use for construction purposes can eliminate the need for temporary construction support facilities. Utilities systems, warehouses, offices, and roads can be built early to use as support facilities for remaining construction.

Construction and procurement times can be reduced by using standardized components and standardized designs.

Standards for materials, equipment, and systems should be selected early in the engineering phase to reduce the possibility of confusion and change later in design or construction. Where possible, the use of commercially available, off-the-shelf components should be used instead of specially designed items. These items are usually time tested, less costly, and have shorter procurement times than specially engineered components. The use of standard designs or designs on the shelf from previous projects can reduce engineering time and cost. Care must be taken to adapt the existing design to the specific site conditions and code requirements of the new project.

The consideration of dimensional limitations of common modes of transportation when designing or specifying project components will minimize the need for special transportation requirements during material delivery and construction Handling oversized items usually adds to the time and cost of delivery to the project site.

The time required for the engineering phase can be reduced by effectively managing the design effort. Strict procedures for the review and approval of proposed changes, engineering submittals, scope changes, and specifications are necessary. Approval cutoff dates and procedures for analysis of schedule and cost impacts of changes and exceptions will help ensure that these steps do not require more time than is necessary to meet project objectives.

Management effort also should be devoted to providing a work environment that is well laid out and comfortable to promote efficiency and productivity in the design office. Techniques to accomplish this objective include efficient lighting, comfortable furniture, workspace layout to ease coordination, dividers to minimize distractions, sound barriers, and background music.

The use of Computer-Aided Design and Drafting (CADD) can save the hours spent at the drafting table producing drawings. Computer drawings can help in engineering, procurement, and construction activities. Color-coding, highlighting, rotating, separating, and zooming aid in visualizing and planning these activities for the most effective use of time. Some CADD software can be used for quantity takeoffs and estimates. The use of CADD requires well trained and experienced personnel to utilize the time saving potential of these systems.

Usually, design drawings are released for construction use as completed drawings in packages. By releasing partially completed drawings containing completed and approved details, procurement, construction planning, and execution can be expedited.

Contractual Approach

An owner with frequent and significant need for new construction or renovation/repair work, and no in-house engineering expertise, can engage in an open-ended contract with an engineering firm whose mission then is to provide

engineering services as required by the owner. Services may include design, construction, construction management, or contract administration. The engineering firm is then familiar with the owner's work and the time needed for engineer or contractor selection is eliminated or reduced.

Contractor prequalification can be done early in the project, well before the time to solicit bids--eliminating the need for a qualification step in the solicitation process. Prequalification also increases the possibility of obtaining a competent contractor, thus minimizing the possibilities of delays or defaults.

The contract documents must be checked for accuracy and completeness before issue to contractors for bidding. Contract document review will help to avoid delays in construction due to errors or omissions. The contract documents also should include milestones, required coordination with other work, work area access, administrative procedures, and requirements for reports.

If material takeoffs are generated during the engineering phase, through the use of CADD or manually, they can be shared with bidders or vendors to minimize the time required for the bid solicitation. The bidding system in Europe and Asia, for instance, uses professional quantity surveyors to establish quantities for the owner. These quantities are included in the bidding documents and used by all prospective bidders.

Each risk should be assigned to the party who is in the best position to control the risk. When risk is fairly allocated in the contract, the contractor can concentrate on the items that he can control and time is not lost in handling disputes. This idea also should be applied to the relationship between the contractor and subcontractors.

The type of contract used affects the project duration. A lump sum contract, in some instances, can speed contract execution. With lump sum contracts, the contractor is usually interested in getting the job done as soon as possible because indirect costs increase with the amount of time the contractor spends on the job. Project scope must be well defined and documentation must be thorough to use a lump sum contract. The use of multiple prime contracts and phased construction can save time by overlapping the design and construction phases. Multiple prime contracts also can save time in the solicitation and bidding process by limiting the need for subcontractors. This approach needs a good construction manager to administer the contracts and control and coordinate the construction. Reimbursable contracts, as opposed to fixed-price contracts, reduce the time for contractor selection because it is not necessary for the contractor to do detailed quantity surveys. Construction costs may be higher, however, because the contractor has less incentive to minimize expenses than in a fixed-price contract.

Incentives can be incorporated into contracts with prime contractors, subcontractors, or material and equipment suppliers to encourage time savings. Bonuses can be paid for completion prior to a specified date at a rate stipulated in the contract. Bonuses are usually paid as a predetermined amount of money for each day that is saved from the specified completion date, not to exceed a certain amount. Penalties and liquidated damages are deducted from the amount due the contractor for each day over the specified duration or completion date.

Fast-tracking can appreciably reduce the total time required to complete a project. Fast-tracking, or phased construction, is the overlapping of project design, procurement, and construction. The design of successive phases of the project is broken into separate work packages that can be put under contract as design of each phase is completed. Contracting can be done with a single general contractor, or with multiple prime contractors. In fast-tracking, early phases of the project can be under construction while later stages are still being designed (3:12).

Regardless of the contract type, the owner should limit involvement in the contractor's work to that which is absolutely necessary to protect the owner's interests. Unnecessary hold-ups for inspections, reviews, and subcontract approvals can cause delays in project completion.

## Scheduling

Various scheduling techniques are available to minimize the time needed for project completion. The schedule should be realistic and should be reviewed and updated regularly to reflect changing situations. The network logic sho d be continually challenged to determine whether there is a more efficient way of sequencing the work. In this way, the schedule is used as a true planning and controlling tool and not just another paperwork requirement. The same type of work can be scheduled in sequence to take advantage of the learning curve--shortening time requirements because of worker experience. Work should be scheduled to match expected weather conditions if possible. If necessary, shelters can be built to continue work during periods of inclement weather.

Total project time can be shortened by "crashing" activities--or to complete the tasks by working extended hours, using multiple shifts, or committing the manpower and equipment necessary to complete the task in the shortest possible time. A task may be crashed by doing the following (10:299-300):

1. Using multiple shifts to complete tasks. Personnel on night shifts are paid premium wages and are generally less productive than workers on the day shift.
2. Working extended hours or extended days. Employees working more than the normal daily or weekly

hours must be paid an overtime premium. Although daily or weekly production will increase by using overtime, the production per hour will decrease.

3. Using larger or additional equipment to accomplish tasks. One of the costs of a piece of equipment is the delivery and return cost. If a piece of equipment is used for only a short time to complete an activity faster, the delivery and return costs can represent a large part of the total cost.
4. Increasing the number of workers on the job. There is a limit to the number of workers who can work on an activity without getting in each other's way. Also, by overmanning an activity, the job may be completed before the workers have a chance to use the learning curve to their advantage. Thus, productivity may actually be lower by adding additional workers to the crew.
5. Using more expensive materials that can be installed faster.

These activity crashing techniques increase the cost of completing the activity as a trade-off for time savings. Mathematical techniques for crashing the schedule are discussed in Chapter Four.

Materials Management

Project time can be reduced by having a single person in charge of coordinating project materials. A materials

coordinator is a staff position whose primary, or only, job is to stay on top of the materials situation at all times. The materials coordinator will maintain material status reports, act as a liaison between construction personnel in the field and procurement personnel, provide advice at weekly planning meetings, coordinate temporary material diversions in emergency situations, and assure the availability of materials as needed.

Optimum efficiency is achieved when materials are delivered to the job site as they are needed without intermediate on-site storage--eliminating the time needed to store the materials. Successful execution of deliveries just as they are needed takes thorough planning, careful coordination, and expediting. Any failure in the system will cause delays since deliveries are scheduled so tightly.

The material laydown area should be planned to best support the construction. Each subcontractor or craft superintendent should have a separate laydown area as close as possible to their work areas. Separate laydown areas provide for better accountability and control, thus minimizing the potential for delays due to the misplacement, damage, or loss of materials that can occur when materials are accessible by multiple parties. The location of laydown areas also can reduce material delivery time.

The use of a special material handling crew to assemble and deliver materials to the work area allows production crews to begin work immediately without wasting time trying

to locate and assemble materials. Additional time can be saved by using barcoding for materials identification. This will help the material handling crew and the production crews to identify materials quickly and properly on site to avoid misuse. Barcoding also provides for more accurate records for the materials coordinator.

Procurement priorities should be established that are consistent with the needs of the project and the capabilities of vendors. These priorities must be communicated to purchasing and expediting personnel so that they can concentrate their attention on the items needed most.

A system to control vendor submittals will decrease the time of material and equipment procurement. A strict policy should be developed to establish "not later than" dates for vendors, suppliers, owner representatives, and engineers for the submittal, review, and approval of documents, shop drawings, and samples. To help insure timeliness, the contract may include incentive or penalty clauses. Typically, an incentive clause may specify the release of 10% of the payment if submittal deadlines are met and the submittals meet the specified quality. For major procurements, submittals should receive strong expediting attention.

The owner may opt to assume responsibility for procurement of selected items so that they can be purchased early in the project to assure their availability when needed. Owner furnished materials should be considered for long lead items and materials needed early in the project.

The prime contractor should consider purchasing materials for subcontractors. If done early, the availability of items to subcontractors when needed may decrease the amount of contract time the subcontractor needs to obtain materials. Lower costs and faster deliveries also may be possible because the prime contractor has the leverage necessary to get better prices than subcontractors.

Construction Work Management

The field Project Manager is often burdened with such a large amount of routine paperwork, reporting, and minor decisions that the important major management functions become neglected. Time can be saved by using an Assistant Project Manager to handle these routine functions, allowing the Project Manager to concentrate on major management functions.

Area Coordinators are staff positions whose function is to coordinate and expedite work in a given area. They operate in a matrix organization, with their area involving the work of several supervisors and trades. Area coordinators have no direct construction responsibilities, but can help in an area by resolving interference problems, coordinating use of space, resolving materials delivery problems, coordinating equipment, and handling other situations that may arise. They report to the project manager and have the authority to issue directives.

A structured change management system should be used to reduce extra costs and loss of time associated with changes.

Each change should be challenged on its need, examined to figure out whether there is a more cost-effective approach to accomplish the purpose of the change, and studied to determine what timing of the change will have the least disruption to the project schedule.

Constructability analyses should continue throughout the construction phase to identify both time and cost savings. For example, if overhead welding is normally require for an activity, decide whether an erection sequence can be used that will allow the component to be welded to be turned upside down for welding. With the constructability reviews, "what if" scenarios involving trial allocations, linear programming, or probability analysis can be used to analyze various approaches to the work to find the one that will yield the greatest time savings.

Proper equipment planning and use is very important in considering ways to complete activities expeditiously. Equipment should be selected that is best suited for fast, safe erection of components. For example, helicopters can be used to position items in high, hard to reach areas, pedestal cranes positioned properly at the start of the project can service large areas, scissors lifts can be used instead of scaffolding, and concrete pumps can be used to place concrete more efficiently. Certain pieces of equipment should be designated as critical and contingency plans should be developed for breakdowns. Contingency plans should include provisions for fast return to service by

maintenance crews or contracted maintenance and a list of locations of potential substitute equipment that can be obtained on short notice.

The job site layout must provide for optimum efficiency and productivity. By using scaled drawings and templates, optimum positioning of construction and personnel facilities can be determined to support construction. Proper site layout can eliminate demotivating factors, reduce distances for movement of materials and equipment, provide the best sequencing for laydown areas throughout the duration of the project, and assure adequate workspace around structures that are to be built.

Quality and productivity on a construction project depend on a motivated work force; therefore, project planning and execution should take into consideration features that make the job site a good workplace. A clean, uncluttered site increases worker motivation and promotes safety. Other key factors include dust control, site drainage to keep workers out of the mud, good work surfaces, well designed parking areas for workers, well placed and shaded toilets, and comfortable facilities for lunch breaks.

Job site pre-assembly is usually more productive, permits better quality control, and saves time in final assembly. Reinforcing steel cages, structural steel assemblies, ducts, concrete formwork, and other components can be pre-fabricated in shop areas that use jigs or assembly

lines. Pre-assembly can be done simultaneously with other work and can continue in inclement weather if done in a protected area.

A common cause of worker delays is lack of tools; therefore, a good tool control program should be developed. The program must provide for monitoring of tool issues, returns, and inventories. Tools must be inspected, maintained, and replaced when necessary. Inventory and issue control can be made quicker and easier with barcoding. Staffing of tool rooms should be structured to fit the project, with the goal of no waiting lines for tool issues--lines mean lost productive work time.

Field Labor Management

Activities requiring heavy use of labor should be reviewed to decide whether substituting equipment for labor is possible. This labor minimization will save both time and labor costs, but will at be at least partially offset by increased equipment costs.

Special shift arrangements can be initiated to get more worker-hours per week. The following are typical examples:

1. Rolling 4-10s. Each crew works four ten-hour days followed by three off days. Work can be done every day by staggering shifts of crews.
2. Variable Length. One crew works four ten-hour days followed a crew that works three thirteen-hour days.

3. 6-10s. A crew works ten-hour days four six days followed by one off day.

4. 3-12s, 3 Off. A crew works three twelve-hour days, has three days off, then repeats the cycle. A second crew alternates the cycle with the first crew.

Efficiency is lost if one crew continues the work started by another crew; therefore, it is advantageous to schedule work so that the same crew does all the work associated with a work package. Responsibility for the work is also clear when one crew does all the work. When using multiple shifts, different work should be planned for each shift.

Specialty crews may be assigned to tasks that support regular shifts and add to their efficiency and productivity. As examples, a night warehouse shift can assemble and preposition materials to be used by crews the next day; grounds maintenance crews can regrade roads, collect refuse, and prepare the site for the next day's work; or a crew can service and repair equipment to be used the next day.

Regular overtime may be planned in the schedule to get more worker-hours per day and avoid additional shifts, but extended overtime can reduce productivity. Occasional overtime may be planned for selected activities to accelerate the schedule or make up for lost time. Spot overtime also may be used to complete a task to avoid running into the next day's work.

Supervisor to worker ratios should be adjusted with changes in the work force or with changes in the criticality or complexity of the work to maintain quality and sufficient control of the work force. The foremen can be involved in the selection of workers for their crews. This application of participatory management can improve crew compatibility and productivity.

A good crew training program that includes pre-work briefings, rehearsals, and cross-training will save time by promoting productivity and reducing rework and also will improve quality. Before assigning crews to new tasks, crews should be briefed on new procedures by using models, visual aids, or demonstrations. Crew input should be allowed to determine the best methods to complete the tasks. The crews can be given formal training and run through rehearsals before the actual work. This technique is particularly applicable to work that involves special safety or health concerns. Cross-training workers in several trades will permit better utilization of their time and can possibly permit a reduction in crew size.

Startup Phase

A comprehensive plan and schedule for systems testing and turnover should be developed early in the construction phase. This plan should address contractor and owner responsibilities. The startup organization should be in place well before it is needed to allow time for startup training

and coordination of completion of construction. The scope of testing should be determined in the engineering phase, with all unnecessary testing eliminated.

# CHAPTER THREE

## TIME VERSUS COST

There are two classifications of costs associated with construction projects, direct costs and indirect costs. Direct costs include the labor, material and equipment operating costs necessary to put work in place. Indirect costs include supervision, job and home office overhead, profit, financing, and the cost of inflation. Direct costs can be allocated to each activity on the project. Indirect costs, on the other hand, can not be realistically prorated and assigned to each separate activity. Indirect costs add up continuously throughout the duration of the project, and if a CPM or precedence network is used for scheduling, can not be divided up among activities, some of which have float.

Total indirect cost on a project increases with time as shown in Figure 3-1. This relationship is not necessarily linear. The actual shape of the curve depends on the complexity of the project and the types of indirect cost involved.

Job overhead and general or home office overhead, a significant part of the total indirect costs, usually increase linearly with time as in Figure 3-2. These costs are normally assumed to be spread out over the entire project with a constant cost per day assigned; however, if the

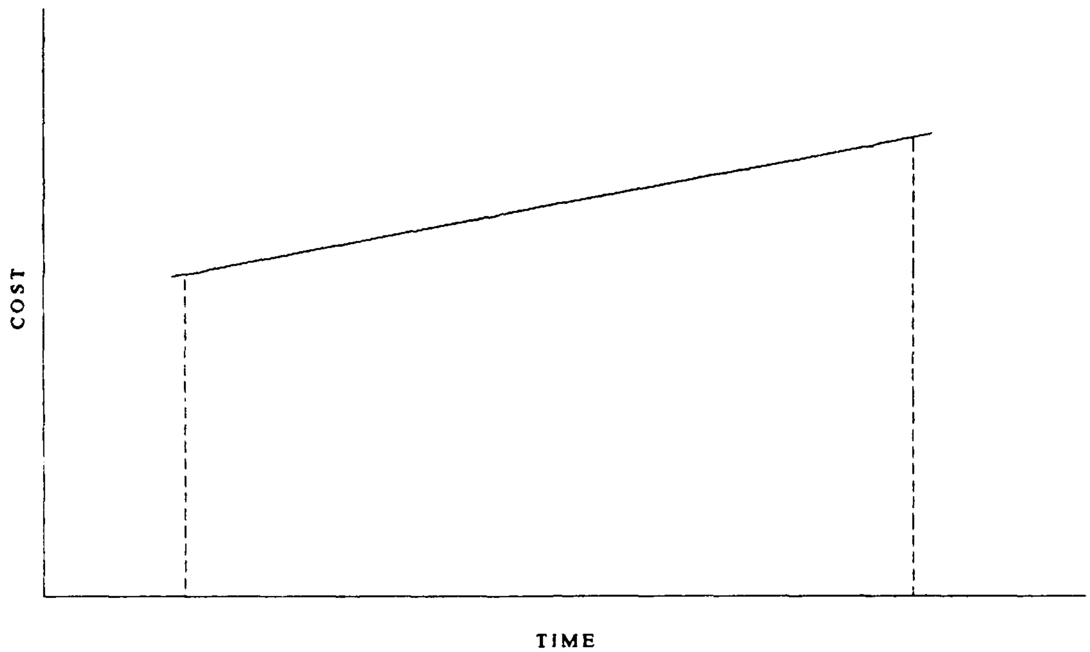


Figure 3-1. Total Indirect Cost

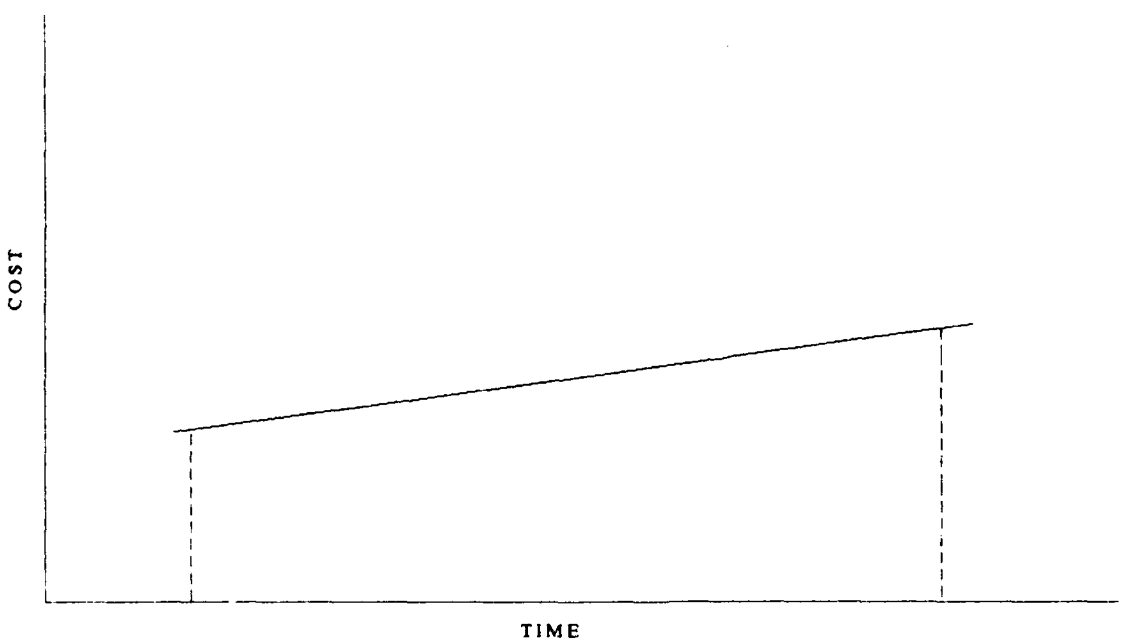


Figure 3-2. Job and General Overhead

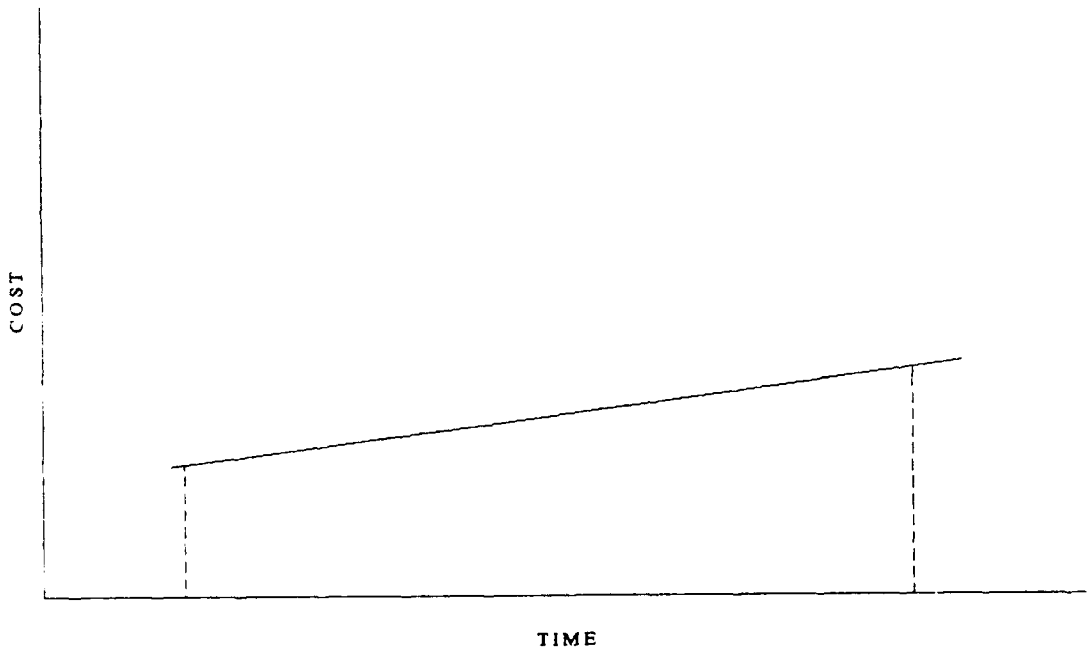


Figure 3-3. Interest Costs

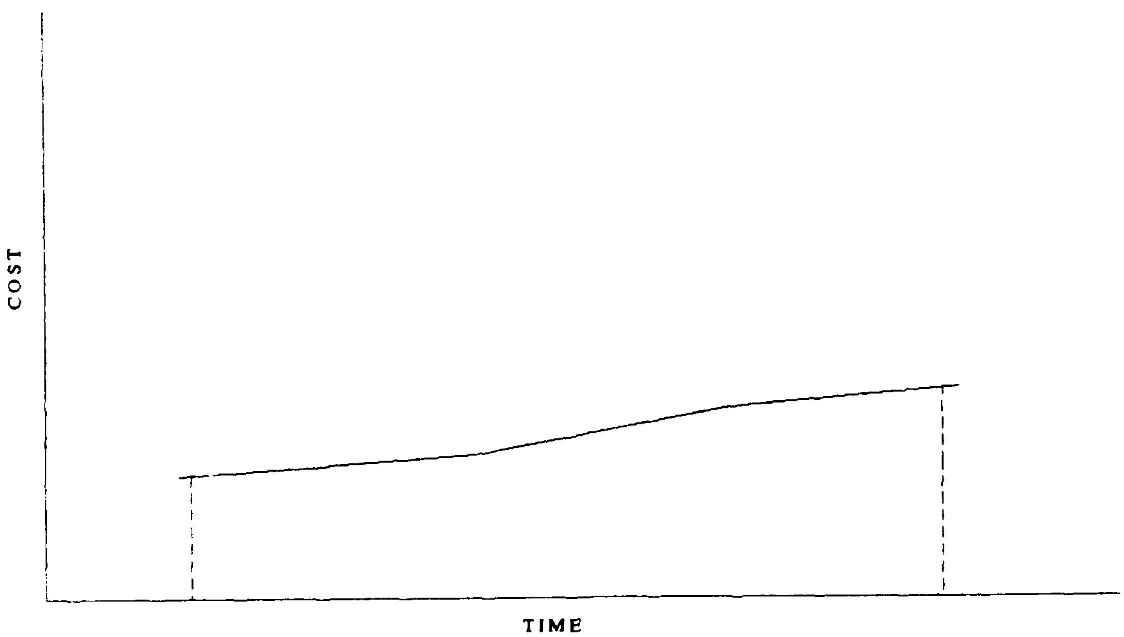


Figure 3-4. Interest Costs, Discontinuous Curve

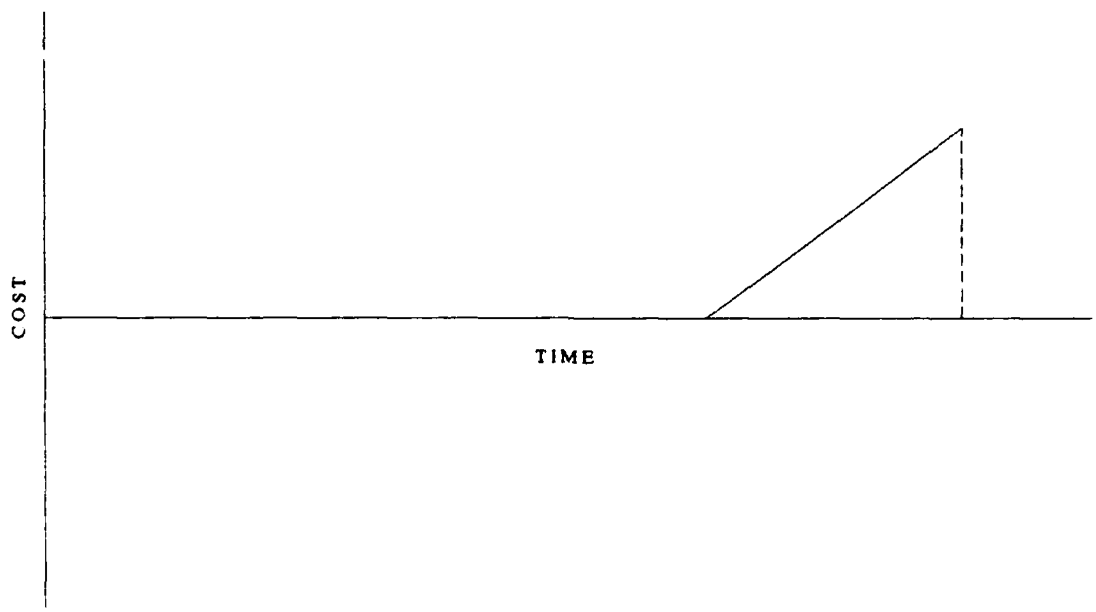


Figure 3-5. Liquidated Damages or Penalty

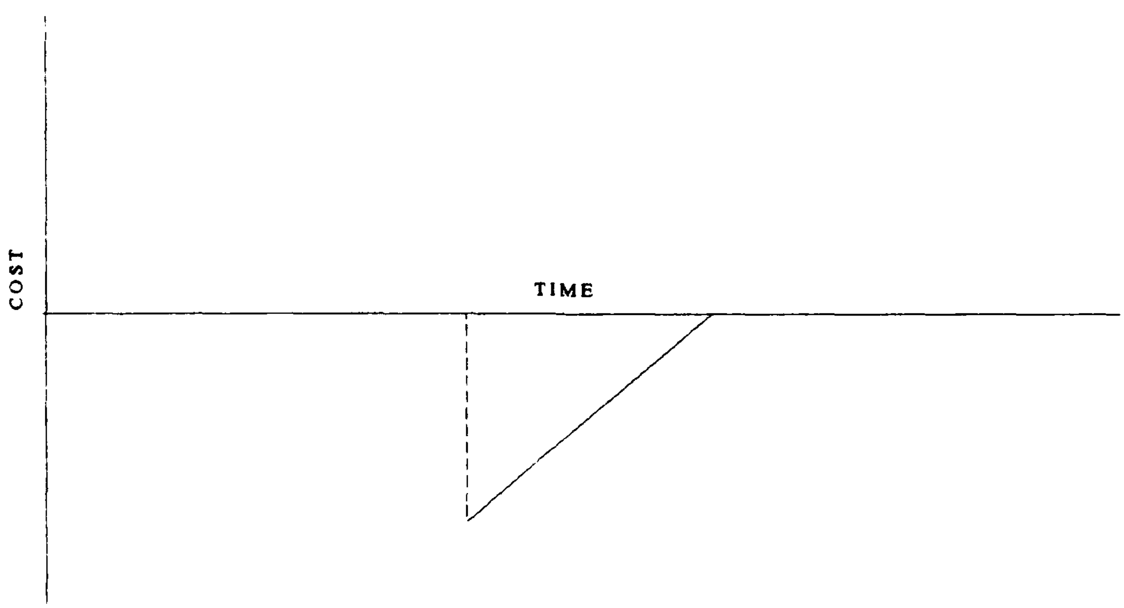


Figure 3-6 . Bonus

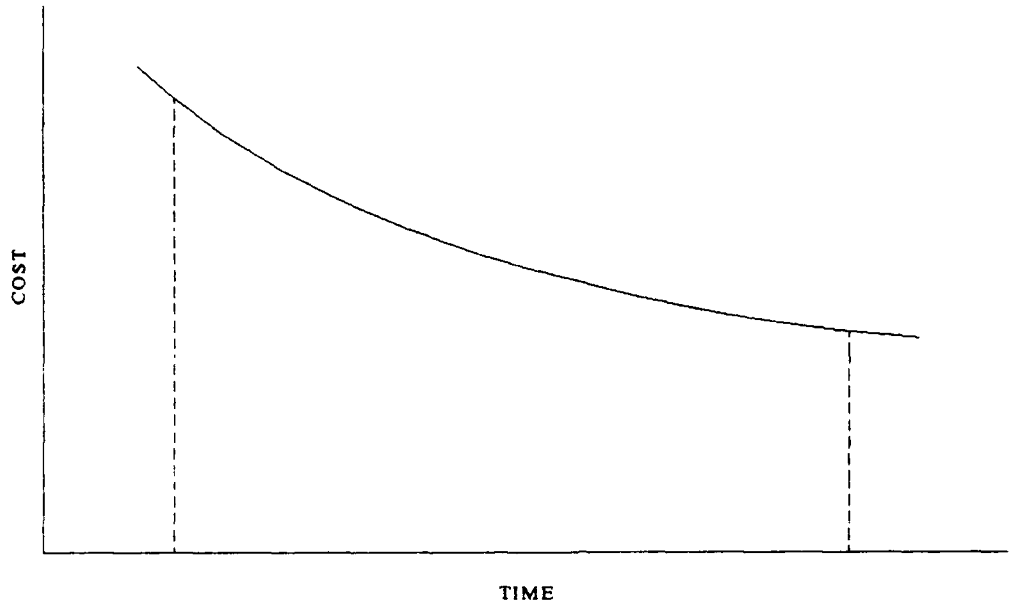


Figure 3-7 . Direct Cost

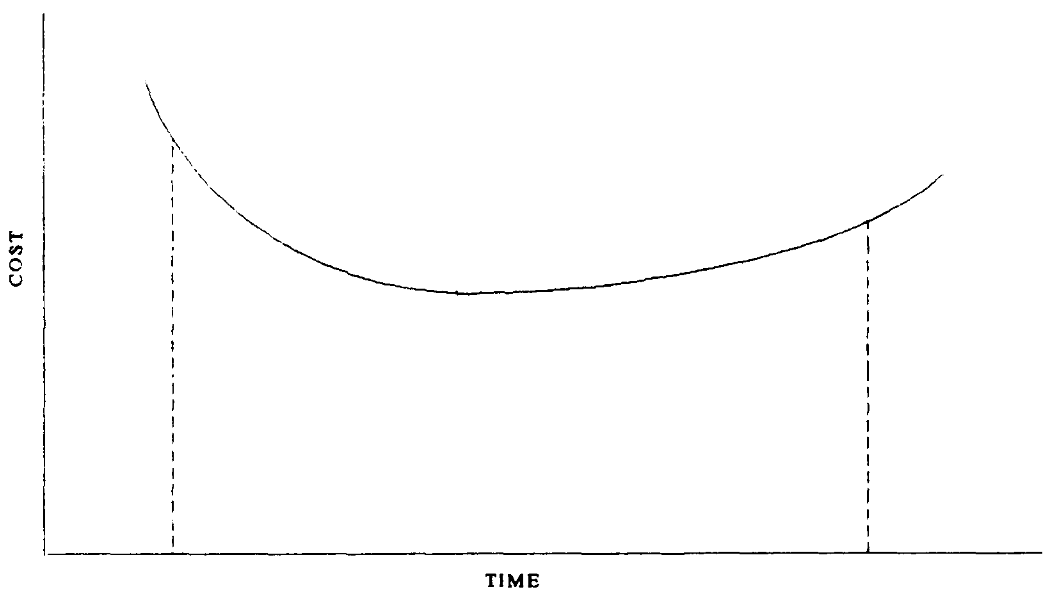


Figure 3-8 . Total Project Cost

all overhead costs equally throughout the project duration, the curve will not be linear and may have points of discontinuity.

Most contractors must borrow money or use credit to finance construction costs. The cost of interest or finance costs increase with project time as shown in Figure 3-3. This relationship is not always linear--the shape will depend on the type of loan or credit extended and the repayment terms. Periodic loans or credit extensions made throughout the project will result in a curve with points of discontinuity such as the one in Figure 3-4.

If the contract specifies liquidated damages or penalties for late completion or bonuses for early completion, the cost of the project as a function of time is effected as shown in Figure 3-5 and Figure 3-6. Since the bonus is an additional payment to the contractor, it is shown as a "negative cost." Shapes of penalty and bonus curves may vary, depending on the particular contract provisions.

The total direct cost will always decrease as project duration increases, as shown in Figure 3-7. Efforts to compress or "crash" activity completion time will result in higher direct cost for each activity. This relationship and methods to determine the direct cost curve will be discussed in detail in Chapter Four.

Once curves for all costs and bonuses or savings are established, they are added together to yield a "Total

Project Cost vs. Time" curve such as the one shown in Figure 3-8. The lowest point on the curve gives the lowest cost project duration. This duration may not be the "ideal duration." There may be other considerations within the company, not involving the project, that the project manager must take into consideration when selecting the ideal project duration.

# CHAPTER FOUR

## SCHEDULE COMPRESSION PROCEDURES

A variety of procedures has been developed to arrive at the direct cost curve shown in Figure 3-7. Procedures for schedule compression or "crashing" from eight different sources were studied and compared. This chapter presents a summary of these procedures.

Before examining the different compression procedures, it is important to understand the definitions of terms that are basic to all procedures:

1. Normal Activity Cost. The minimum direct cost of an activity determined by the estimator during project planning, based on the company's experience, methods, and assets.
2. Normal Activity Duration. The time needed to complete an activity at the normal direct cost.
3. Activity Crash Duration. The shortest possible time in which an activity can be completed.
4. Activity Crash Cost. The cost associated with the crash duration.
5. Normal Project Cost. The direct cost of the project with all activities "normal."
6. Normal Project Duration. The project duration with all activities "normal."

7. Project Crash Cost. The direct cost of the project with all possible activities "crashed."

8. Project Crash Duration. The project duration with all possible activities "crashed."

Activity Time-Cost Relationships

One procedure to find the relationship between the time and cost of an activity and develop activity time-cost curves is as follows (1:326):

1. Select several methods to perform an activity.

2. Determine the duration and direct cost for each method.

3. Plot the results of step 2 on a graph of time versus direct cost.

4. Connect the points on the graph with straight lines as follows: Starting with the lowest cost point, draw a straight line to the next point. This line represents the cost slope between these two points. From the second point, draw a line to the third point, and so on, until the highest point is connected. The lines represent the cost slope between each two consecutive points.

The cost slope ($\delta$) represents the cost of reducing the duration of an activity by one day.

$$\delta = \frac{\text{crash cost - normal cost}}{\text{normal duration - crash duration}}$$

There are four possible relationships that can exist between the time and cost of an activity (1:328-329):

1. Linear Relationship Between Time and Cost. The additional cost per day is uniform over the entire period. See Figure 4-1.
2. Linear Relationship Associated with Different Time Intervals. The additional cost per day is not uniform over the entire period. There may be two or more cost slopes associated with this case. See Figure 4-2.
3. Discrete Function. There is no relationship between normal and crash costs. There is no slope in this relationship. Either the normal cost and duration or the crash cost and duration are used in the network compression. See Figure 4-3.
4. Nonlinear Continuous Function. No straight line relationship exists between the normal and crash costs. The relationship between time and cost is represented by a continuous curve. See Figure 4-4.

For greatest accuracy in finding the time versus cost curve, enough points must be plotted to find the true shape of the curve. However, calculating various costs and durations for individual activities is time consuming and sometimes difficult. Often, only two points are determined--the normal point and the crash point--and the relationship is assumed to be linear. By assuming this linear relationship,

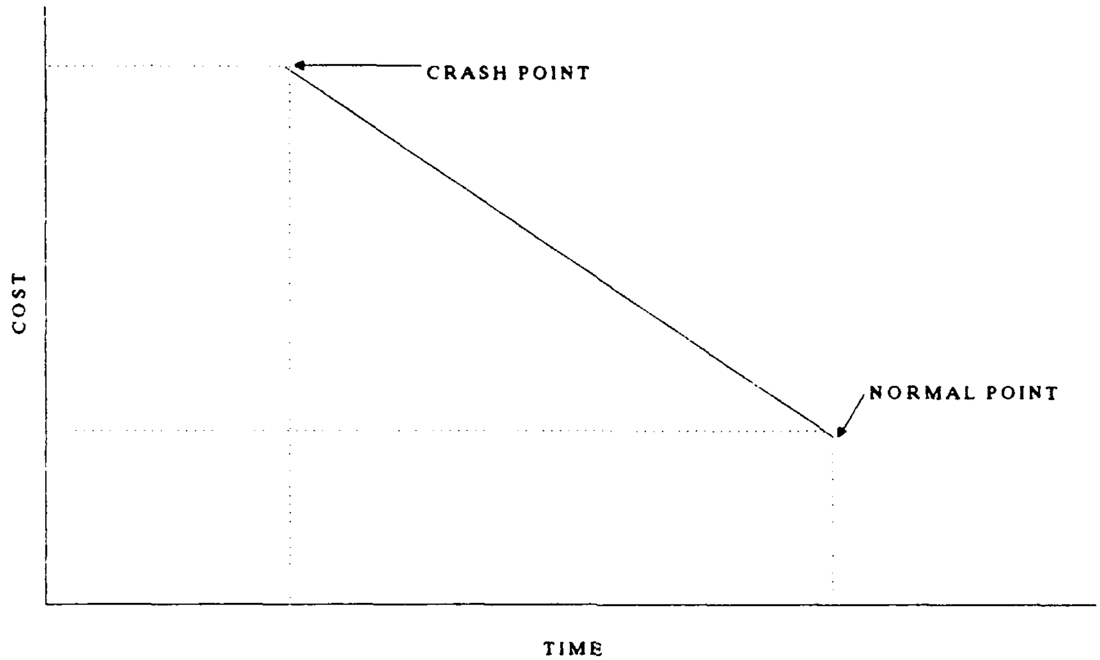


Figure 4-1. Linear Relationship Between Time and Cost

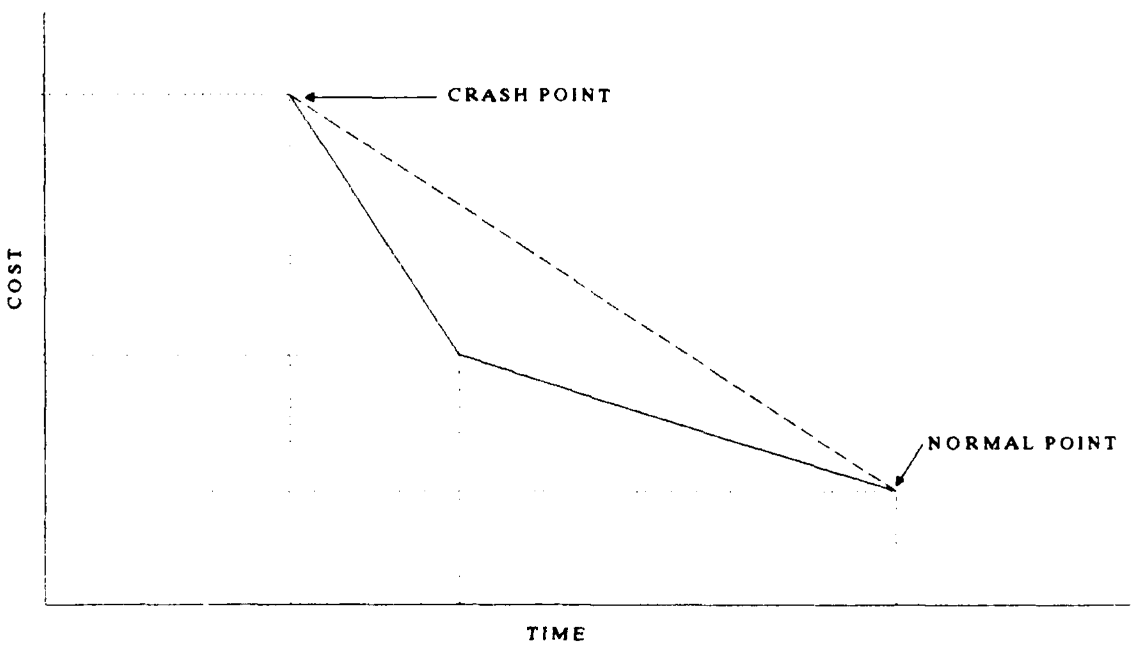


Figure 4-2. Linear Relationship Associated with Different Time Intervals

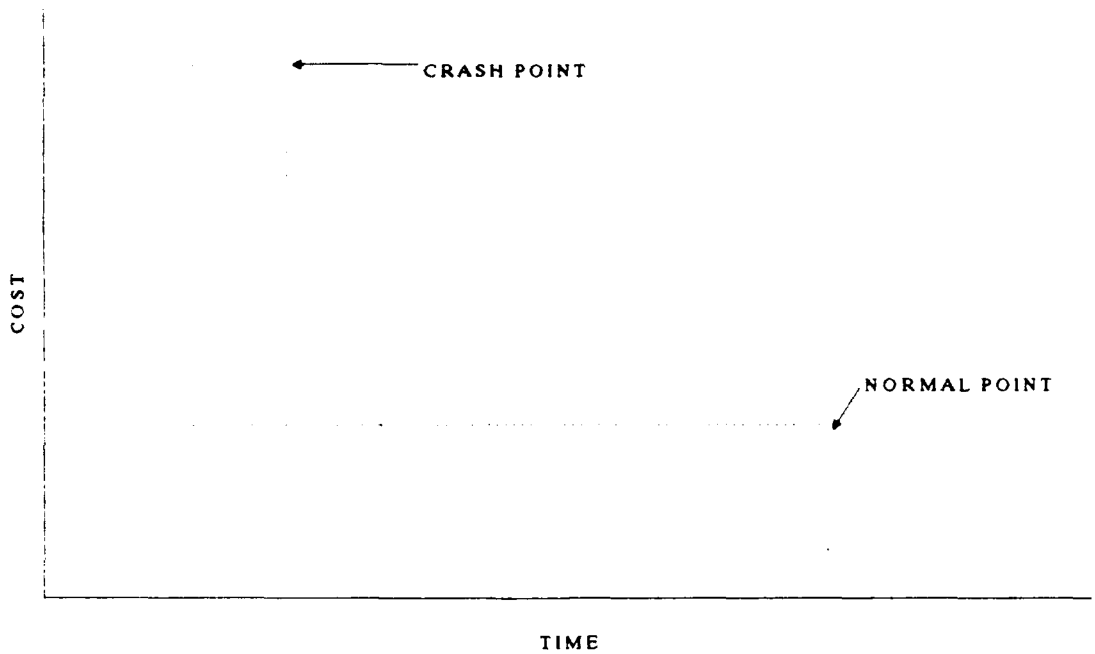


Figure 4-3. Discrete Function

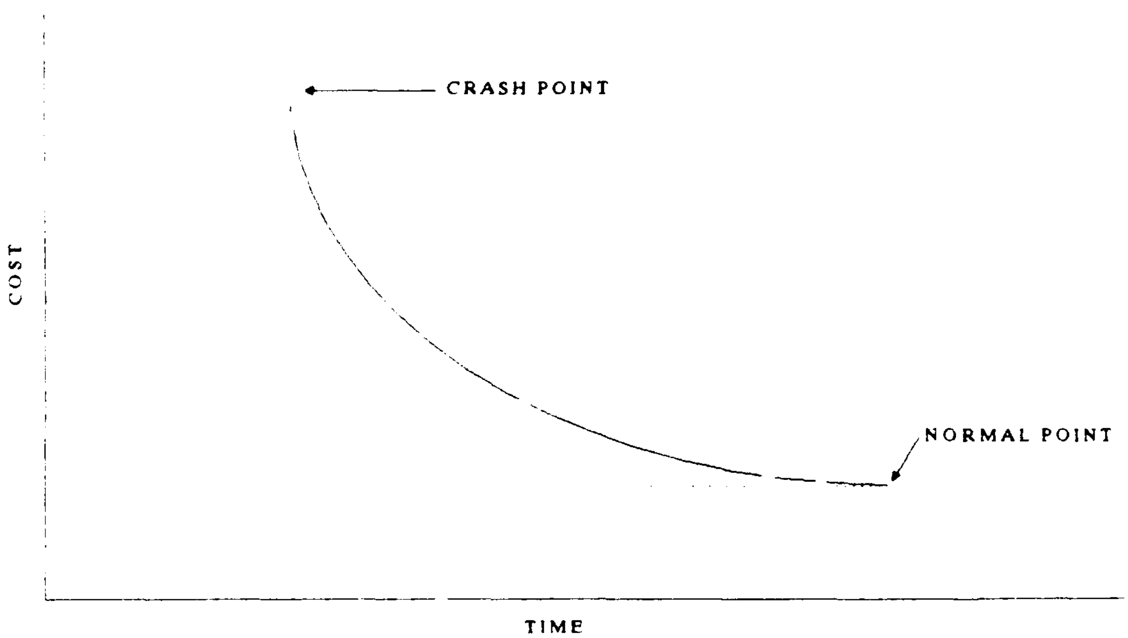


Figure 4-4. Nonlinear Continuous Function

it is not necessary to plot results on a curve--the cost slope can be determined by equation.

The compression methods described below are based on a linear relationship between activity time and cost. They can be adapted for use with other time-cost relationships, if desired, by assigning more than one cost slope to an activity. In this case, the cost slope would change throughout the available crash time of the activity.

Herbsman Method

The Herbsman method of schedule compression can be used with the arrow diagram or the precedence diagram and consists of the following steps (6):

1. Construct the network for the project.
2. Calculate the normal time and normal cost for each activity.
3. Calculate the crash time and crash cost for each activity. Annotate the network diagram with the activity crash durations.
4. Using the network logic established in step 1, find the normal project duration and normal project cost.
5. Using the network logic, find the project crash duration and the project crash cost.
6. Calculate the cost slope ($\delta$) for each activity that can be crashed. Annotate each activity $\delta$ on the normal network diagram.

7. Find the critical path using the normal network.

8. Find the activity on the critical path that has the smallest $\delta$. If there are two critical paths, choose the activity with the smallest $\delta$ on each critical path.

9. Reduce the duration of the activity found in step 8 by one day. This results in a reduction of the project of one day. If there are two critical paths, reduce the activity found in step 8 for each critical path by one day.

10. Calculate the resulting project cost by adding the cost slope used in step 8 to the normal project cost. The results can be entered into a summary table such as the one shown in Figure 4-5, and then plotted.

| Project Duration | Action Taken | Cost |
|---|---|---|
| 21 | ----- | 8900 |
| 20 | ACTIVITY A: 1 DAY | 9000 |
| 19 | A: 1 DAY | 9100 |
| 18 | A: 1 DAY | 9200 |
| 17 | B: 1 DAY | 9400 |
| 16 | B: 1 DAY, D: 1 DAY | 9900 |

Figure 4-5. Compression Summary Table

11. Mark the new activity durations on the network diagram. Recalculate the network using the reduced activity duration(s). If the resulting project time equals the project crash time found in step 5, the procedure is complete. If not, go on to step 12.

12. Find the critical path of the revised network.

13. Go to step 8.

The Herbsman method is easy to understand and follow. Project compression is done primarily by using the network diagram and one table. This method works well with scheduling software for network calculations and critical path determinations.

Finding the project crash time and cost before starting the compression cycles is an extra step, but if the network is small or a computer is used, the network calculations do not take long. Knowing the project crash duration ahead of time provides a good check in determining when compression is complete. The total crash cost serves no useful purpose, except for comparison.

<u>Ahuja Method</u>

The Ahuja method of schedule compression assumes the network arrow diagram is complete and involves the following steps (1:333-338):

1. Find the normal project duration and the normal project cost.

2. Find the normal duration critical path using network logic.

3. Using the criticality theorem, eliminate all noncritical activities that do not need to be crashed. A skeleton network is redrawn without these activities. In simple terms, the criticality theorem is as follows: $C_1$ and $C_2$ are two parallel paths (or two paths with common end nodes when using an arrow diagram), where the normal duration of path $C_1$ is greater than the normal duration of path $C_2$. If the crash duration of path $C_1$ is greater than the normal duration of path $C_2$, path $C_2$ is the greater path and its activities need not be considered for crashing. On the other hand, if the crash duration of path $C_1$ is not greater than the normal duration of path $C_2$, activities on path $C_2$ must be considered in combination with activities on path $C_1$.

4. Tabulate normal and crash durations and normal and crash costs for all the activities.

5. Calculate and tabulate the cost slope for each activity.

6. Shorten critical activities beginning with the activity with the lowest cost slope. Shorten each activity by one day until (a) its crash time is reached or (b) a new critical path is formed.

7. When a new critical path is formed, shorten the combination of activities with the lowest combined slope.

8. At each step, check to see if float has been introduced in any activities. If so, these activities' durations can be expanded to reduce cost.

9. After each shortening cycle, compute the new project cost and duration, and plot on a time-cost graph.

10. Continue until no further compression is possible.

The Ahuja method, which can be used with a precedence network, is straightforward and simple, except when it comes to the use of the "criticality theorem." This is an unnecessary step that adds more work and complexity to the procedure. Additional care also must be taken not to forget the activities eliminated by the criticality theorem when computing the new project cost after each compression cycle. The only apparent value in the criticality theorem is in scaling down the network diagram; however, if a computer is used for network calculations, eliminating activities is not necessary.

Antill/Woodhead Method

The Antill/Woodhead method of schedule compression uses the following steps and assumes the network arrow diagram is complete (2:75-84):

1. Calculate the normal and crash costs and durations for all activities.
2. Calculate the cost slope for each activity.
3. Annotate the network diagram with normal and crash durations, normal cost, and cost slope.
4. Find the critical path of the normal network.
5. List the activities on the critical path.
6. Delete activities that have no potential for compression, including those whose normal and crash durations are equal and those that have been previously crashed.
7. Select the activity with the smallest cost slope. If two critical paths exist, select the activity with the smallest slope from each critical path.
8. Determine the amount by which the activity selected in step 7 can be compressed and the cost. In other words, find the difference between the normal duration and the crash duration and the cost to compress.
9. Figure out if any network limitations to the amount of compression in step 8 exist and why the limitations exist. For instance, a network limi-

tation would exist if a parallel path has a float that is shorter than the proposed amount of compression.

10. Carry out the compression within the limitations determined in step 9. When all activities on the critical path(s) reach their crash durations, stop--it is physically impossible to compress further on the critical path. There is no advantage in crashing non-critical activities since they will have no effect on the project duration.

11. Compute the new project duration and the new project cost. These can be plotted on the time-cost graph.

12. Find the new critical path and go to step 6.

This method is simple and easy to follow. It can be easily adapted to a precedence network. The procedure is very similar to the Herbsman method in its reliance on the network diagram for recording and changing project data and determining activities to crash.

Determining the number of days that an activity can be crashed and checking the network for limitations (steps 7 and 8) reduces the number of cycles needed to complete the project compression, but involves more analysis of the network during each cycle.

O'Brien Method

The O'Brien method of schedule compression assumes the project arrow diagram is completed and uses the following steps (8:171-177):

1. Find the normal activity costs and normal activity durations.
2. Determine the activity crash costs and activity crash durations.
3. Find the normal project cost and the normal project duration.
4. Calculate the cost slope for each activity.
5. Tabulate project data as shown in the first six columns in Figure 4-6.
6. Make the table of activity durations as shown in Figure 4-7.
7. On the table of possible costs (Figure 4-8), list the cost of shortening one day along each critical path. The critical path is identified from the previous float column in Figure 4-6. Check Figure 4-7 to see which activities on the path can be shortened.
8. Select the activities to be crashed by low slope and early location in the network. Circle the selection on Figure 4-8 and total the circled costs.
9. Revise the durations on Figure 4-7.

| Activity | Duration, days | | Cost | | Cost | Float time remaining as project time (P) is reduced | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| i-j | Normal | Crash | Normal | Crash | Slope | 34 | 33 | 32 | 31 | 39 | 29 | 28 | 27 | 26 | 25 | 24 |
| 0-1 | 3 | 2 | $2,000 | $2,500 | $500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1-2 | 2 | 1 | 400 | 500 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2-3 | 2 | 1 | 1,500 | 1,800 | 300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3-4 | 15 | 8 | 5,000 | 7,100 | 300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3-6 | 4 | 3 | 800 | 1,000 | 200 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3-9 | 10 | 6 | 6,000 | 8,000 | 500 | 4 | 4 | 3 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| 3-10 | 1 | 1 | 300 | - | - | 13 | 13 | 12 | 12 | 11 | 10 | 9 | 9 | 8 | 7 | 6 |
| 3-12 | 6 | 4 | 2,400 | 3,000 | 300 | 16 | 16 | 15 | 15 | 14 | 13 | 12 | 12 | 11 | 10 | 9 |
| 4-5 | 2 | 1 | 400 | 900 | 500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5-8 | 8 | 6 | 2,500 | 3,000 | 250 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6-7 | 10 | 8 | 7,500 | 8,500 | 500 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7-8 | 10 | 8 | 1,500 | 1,800 | 150 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8-13 | 2 | 1 | 300 | 400 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9-11 | 5 | 3 | 1,000 | 1,200 | 100 | 4 | 4 | 3 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| 10-11 | 5 | 4 | 1,500 | 1,800 | 300 | 13 | 13 | 12 | 12 | 11 | 10 | 9 | 9 | 8 | 7 | 6 |
| 11-12 | 3 | 2 | 8,000 | 8,500 | 500 | 4 | 4 | 3 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| 12-13 | 5 | 2 | 4,000 | 8,000 | 1,333 | 4 | 4 | 3 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |

Figure 4-6. Table of Project Data

| Activity | Duration, days | | Project length | | | | | Means duration at crash value | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| i-j | Normal | Crash | 33 | 32 | 31 | 30 | 29 | 28 | 27 | 26 | 25 | 24 |
| 0-1 | 3 | 2 | | | | | | | 2 | | | |
| 1-2 | 2 | 1 | 1 | | | | | | | | | |
| 2-3 | 2 | 1 | | | | 1 | | | | | | |
| 3-4 | 15 | 8 | | | | | | 14 | | 13 | 12 | 11 |
| 3-6 | 4 | 3 | | | | | | 3 | | | | |
| 3-9 | 10 | 6 | | | | | | | | | | |
| 3-10 | 1 | 1 | | | | | | | | | | |
| 3-12 | 6 | 4 | | | | | | | | | | |
| 4-5 | 2 | 1 | | | | | | | | | | |
| 5-8 | 8 | 6 | | | 7 | | 6 | | | | | |
| 6-7 | 10 | 8 | | | | | | | | | 9 | 8 |
| 7-8 | 10 | 8 | | | | | 9 | 8 | | | | |
| 8-13 | 2 | 1 | | 1 | | | | | | | | |
| 9-11 | 5 | 3 | | | | | | | | 4 | 3 | |
| 10-11 | 5 | 4 | | | | | | | | | | |
| 11-12 | 3 | 2 | | | | | | | | | | 2 |
| 12-13 | 5 | 2 | | | | | | | | | | |

Figure 4-7. Revised Activity Duration Table

| Activity | Cost | Project days | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 33 | 32 | 31 | 30 | 29 | | 28 | | | 24 | | | 23 | | |
| | | Critical Path | | | | | | | | | | | | | | |
| i-j | Slope | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | | 1 | 2 | 3 | 1 | 2 | 3 |
| 0-1 | $500 | 500 | 500 | 500 | 500 | 500 | | 500 | | | * | | | * | | |
| 1-2 | 100 | 100 | * | * | * | * | | * | | | * | | | * | | |
| 2-3 | 300 | 300 | 300 | 300 | 300 | * | | * | | | * | | | * | | |
| 3-4 | 300 | 300 | 300 | 300 | 300 | 300 | | 300 | | | 300 | | | 300 | | |
| 3-6 | 200 | | | | | | 200 | | 200 | | | * | | | * | |
| 3-9 | 500 | | | | | | | | | | | | 500 | | | 500 |
| 3-10 | - | | | | | | | | | | | | - | | | - |
| 3-12 | 300 | | | | | | | | | | | | | | | |
| 4-5 | 500 | 500 | 500 | 500 | 500 | 500 | | 500 | | | 500 | | | 500 | | |
| 5-8 | 250 | 250 | 250 | 250 | 250 | 250 | | * | | | * | | | * | | |
| 6-7 | 500 | | | | | | 500 | | 500 | | | 500 | | | * | |
| 7-8 | 150 | | | | | | 150 | | 150 | | | * | | | * | |
| 8-13 | 100 | 100 | 100 | * | * | * | | * | | | * | | | * | | |
| 9-11 | 100 | | | | | | | | | | | | * | | | * |
| 10-11 | 300 | | | | | | | | | | | | | | | |
| 11-12 | 500 | | | | | | | | | | | | 500 | | | 500 |
| 12-13 | 1333 | | | | | | | | | | | | 1333 | | | 1333 |
| Least expensive compression cost | | 100 | 100 | 250 | 300 | | 400 | | 450 | | | 1300 | | None possible along C.P. 2 | | |

Activity expedited on day

* Activity at crash duration

Figure 4-8. Table of Possible Costs

10. Recheck the critical path(s) and revise floats as necessary on Figure 4-6.

11. Repeat steps 7 to 10 to compress by another day. When there are no more possible activities to crash on one of the critical paths, compression is complete. The project cost corresponding to each project duration can be calculated by adding the total daily crash costs from Figure 4-8 to the normal project cost. This data can then be plotted on the time-cost graph.

The use of three different tables makes this method cumbersome and difficult to follow. Moving from table to table can become confusing. With a very large net.ork, these tables would be unwieldy. The use of these tables seems unnecessary since the network diagram is used as part of the compression procedure.

## Moder/Phillips Method

The Moder/Phillips method of schedule compression assumes the logical network diagram is completed and uses the following steps (7:109-117):

1. Determine the normal activity durations and the normal activity costs.
2. Determine the activity crash durations and activity crash costs.
3. Calculate the cost slope for each activity.

4. Find the normal project duration and normal project cost from the network.
5. Find the critical path of the network.
6. If the network has two or more critical paths, proceed directly to step 8. If there is a single critical path, consider critical path activities, and augment the activity with the lowest cost slope. "Augment" means to crash the activity's duration completely, or to decrease the duration by the difference between the normal duration and the crash duration. If this augmentation causes the current critical path to become sub-critical, do not make the augmentation, but go to step 7.
7. Let $\delta t_c$ equal the smallest reduction in the duration of the critical path that makes one or more additional paths become critical. Consider all activities on the current critical path for which $\delta t \geq \delta t_c$, and augment the activity with the lowest cost increase, rather than the lowest slope. The cost slope of the chosen activity is $\delta c_m/\delta t_m$. If $\delta t_m = \delta t_c$, the augmentation cycle is completed. If $\delta t_m > \delta t_c$, then this augmentation causes the current critical path to go subcritical by an amount designated as $\delta t_{sc}$. In this situation, identify activities that can be sold back--activities on the newly formed subcritical path that have been most recently augmented on previous

cycles, and for which $\delta t \leq \delta t_{sc}$. The resulting cost slope for step 7 is then $(\delta c_m - \delta c_{sold\ back})/\delta t_m$. Go to step 9.

8. Divide the activities that lie on the critical paths into two subsets, I and II. Subset I contains only activities common to both critical paths. Subset II contains activities not common to all critical paths.

   (a) Apply step 6, or step 7 if necessary, to subset I to find the optimum augmentation.

   (b) To get a project duration reduction by augmenting subset II activities, two or more activities have to be augmented simultaneously. The cost slope of subset II activities will be the sum of the augmentation costs of two or more activities, less costs associated with activities sold back as described in step 7, divided by the reduction in duration achieved by the simultaneous augmentations.

   (c) From the augmentations in steps 8a and 8b, select the one with the lowest cost slope.

9. Tabulate results and plot the points on a time-cost graph.

10. Repeat steps 5 to 9 until all the activities on one of the critical paths reach their crash durations, at which time the project compression is complete.

This method is confusing and difficult to follow. Determining which activity to crash during each cycle is a major undertaking that does not have to be so complex. Over-crashing activities without regard to network limitations, and "selling back" time on other activities is not a very efficient way of accomplishing compression. This technique creates more work, wastes time, and adds to the confusion of the procedure.

## Harris Method

The Harris method of schedule compression uses the Fondahl technique. This method assumes the logical network is constructed. Harris presents three procedures to arrive at the minimum cost curve for a project; (1) minimum cost curve from normal start, (2) minimum cost curve from all crash start, and (3) minimum cost curve from conventional estimate start. Since the other techniques studied start compression procedures from the normal condition, only procedure (1) will be summarized here to facilitate a comparison of the methods. The steps in this method begin after the normal project cost and duration are found, and activity crash costs and durations are determined (5:208-221):

1. Each cycle starts with the selection of the proper combination of activities to be changed from an Activity Selection and Tally Table (Figure 4-9)

| Combination Selection | | | | | ACT | $ Slope | CP CY | FIN CY | T | △T | Revised T / △ T | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 4 | 3 | 2 | 1 | | | | | | | 1 | 2 | 3 | 4 | 5 |
| | | | | | 10 | -- | 0 | 0 | 5 | -- | | | | | |
| | | | | X | 20 | 150 | 0 | 1 | 3 | 2 | 1 / 0 | | | | |
| | | | X | | 60 | 200 | 0 | 2 | 2 | 1 | | 1 / 0 | | | |
| | | X | | | 70 | 200 | 0 | 3 | 3 | 1 | | | 2/0 | | |
| X | X | | | | 30 | 300 | 0 | 6 | 7 | 3 | | | | 6 / 2 | 5 / 1 |
| | | | | | 44 | 300 | 7 | 11 | 5 | 2 | | | | | |
| 300 | 300 | 200 | 200 | 150 | | | | | | | | | | | |

Figure 4-9. Activity Selection and Tally Table

| Step | Activity | 0 | 1 | 2 | 3 | 4 | 5 | | 6 | | 7 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 10 | ~~10~~ | ~~10~~ | ~~10~~ | ~~10~~ | ~~10~~ | ~~10~~ | ~~10~~ | ~~10~~ | ~~10~~ | ~~10~~ | ~~10~~ | ~~10~~ |
| 2 | 20 | 20 | ~~20~~ | ~~20~~ | ~~20~~ | ~~20~~ | ~~20~~ | ~~20~~ | ~~20~~ | ~~20~~ | ~~20~~ | ~~20~~ | ~~20~~ |
| 3 | 30, 32 | 30 | 30 | 30 | 30 | 30 | 30 | 32 | ~~30~~ | 32 | ~~30~~ | 32 | 32 |
| 4 | 40, 42, 44 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 42 |
| 5 | 50, 52 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| 6 | 60 | 60 | 60 | ~~60~~ | ~~60~~ | ~~60~~ | ~~60~~ | ~~60~~ | ~~60~~ | ~~60~~ | ~~60~~ | ~~60~~ | ~~60~~ |
| 7 | 70 | 70 | 70 | 70 | ~~70~~ | ~~70~~ | ~~70~~ | ~~70~~ | ~~70~~ | ~~70~~ | ~~70~~ | ~~70~~ | ~~70~~ |

Figure 4-10. Tally of Critical Paths at End of Cycle

| | Combination | | | T Change | | | | Days | $ | $ | Project | Project |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CY | 1 | 2 | 3 | 1 | 2 | 3 | NL | Changed | Slope | Changed | Cost | Days |
| 0 | | | | | | | | | | | $16,000 | 30 |
| 1 | 20 | | | 2 | | | None | 2 | 100 | 200 | $16,200 | 28 |
| 2 | 60 | | | 1 | | | None | 1 | 150 | 150 | $16,350 | 27 |
| 3 | 70 | | | 1 | | | None | 1 | 150 | 150 | $16,500 | 26 |
| 4 | 30 | | | 3 | | | 1 | 1 | 250 | 250 | $16,750 | 25 |
| 5 | 30 | | | 2 | | | 1 | 1 | 250 | 250 | $17,000 | 24 |
| 6 | 30 | 32 | | 1 | 2 | | None | 1 | 400 | 400 | $17,400 | 23 |
| 7 | 40 | | | 3 | | | 1 | 1 | 400 | 400 | $17,800 | 22 |
| 8 | 50 | 52 | | 5 | 2 | | None | 2 | 650 | 1300 | $19,100 | 20 |
| 9 | 50 | 52 | | 3 | 2 | | None | 2 | 800 | 1600 | $20,700 | 18 |
| 10 | 50 | 44 | | 1 | 3 | | 2 | 1 | 850 | 850 | $21,550 | 17 |
| 11 | 40 | 42 | 44 | 2 | 2 | 2 | None | 2 | 1100 | 2200 | $23,750 | 15 |

Figure 4-11. Compression Summary Table

| Cycle | | | | | 1 | | | 2 | | | 3 | | | 4 | | | 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Activity Changed | | | | | 20 | | | 60 | | | 70 | | | 30 | | | 30 | | |
| Network Limit | | | | | None | | | None | | | None | | | 1 | | | 1 | | |
| Days Changed | | | | | 2 | | | 1 | | | 1 | | | 1 | | | 1 | | |
| Link | | I | J | LAG | I | J | LAG | I | J | LAG | I | J | LAG | I | J | LAG | I | J | LAG |
| I | J | EFD | ESD | | | | | | | | | | | | | | | | |
| 10 | 20 | 5 | 5 | 0 | < | < | | | | | | | | | | | | | |
| 20 | 30 | 8 | 8 | 0 | < | < | | | | | | | | | | | | | |
| 20 | 32 | 8 | 8 | 0 | < | < | | | | | | | | | | | | | |
| 30 | 40 | 15 | 15 | 0 | < | < | | | | | | | | < | < | | < | < | |
| 30 | 42 | 15 | 15 | 0 | < | < | | | | | | | | < | < | | < | < | |
| 32 | 40 | 13 | 15 | 2 | < | < | | | | | | | | | < | 1 | | <* | 0 |
| 32 | 42 | 13 | 15 | 2 | < | < | | | | | | | | | < | 1 | | <* | 0 |
| 32 | 44 | 13 | 13 | 0 | < | < | | | | | | | | | | | | | |
| 40 | 50 | 21 | 21 | 0 | < | < | | | | | | | | < | < | | < | < | |
| 40 | 52 | 21 | 21 | 0 | < | < | | | | | | | | < | < | | < | X | 1 |
| 42 | 50 | 20 | 21 | 1 | < | < | | | | | | | | < | < | | < | < | |
| 42 | 52 | 20 | 21 | 1 | < | < | | | | | | | | < | < | | < | X | 2 |
| 44 | 52 | 20 | 21 | 1 | < | < | | | | | | | | | <* | 0 | | X | |
| 50 | 60 | 31 | 31 | 0 | < | < | | | | | | | | < | < | | < | < | |
| 52 | 60 | 29 | 31 | 2 | < | < | | | | | | | | < | < | | X | < | 1 |
| 60 | 70 | 33 | 33 | 0 | < | < | | < | < | | | | | < | < | | < | < | |

Figure 4-12. Network Limit Determination Table

and a Tally Table (Figure 4-10). Three conditions have to be satisfied in selecting activities:

a. The activity or activities must be critical and, if shortened, must shorten all critical paths.

b. The activity or activities must have the smallest current cost slope.

c. The activity or activities must be available for shortening. In other words they cannot have reached their crash time.

2. Data from the Activity Selection and Tally Table is entered in the Summary Table (Figure 4-11).
3. The network limit is determined in a Network Determination Table (Figure 4-12).
4. The network limit is entered in the Summary Table and a new time-cost curve is established for the project.
5. The Network Limit Determination Table is updated.
6. The project network is updated.
7. The Activity Selection and Tally Table is updated.
8. The Critical Path Tally is updated.
9. The process is repeated until all the activities on the critical path(s) have reached their crash times.

This method, with its use of the network diagram and four tables to compress the project, is even more confusing than the O'Brien method. The tables for selections and

tallies are complicated and cumbersome. With a large network, confusion can develop when transferring data from table to table.

<u>Radcliffe/Kawal/Stephenson Method</u>

The Radcliffe/Kawal/Stephenson method of schedule compression assumes that the normal network plans are complete and the critical path is identified. The procedure also assumes that the normal activity cost, normal activity duration, activity crash cost, activity crash duration, and the cost slopes for each activity have been determined. This method includes the following steps (9:114-117):

1. Enter data in the Utility Data Table shown in Figure 4-13.

| Activity | Available Crash Time | Cost Slope | Normal Cost |
|---|---|---|---|
| A | 1 | $10 | $360 |
| B | 2 | $50 | $1100 |
| C | 2 | $40 | $1900 |
| D | 1 | $20 | $1500 |
| E | 3 | $20 | $1400 |
| F | 0 | -- | $740 |

Figure 4-13. Utility Data Table

2. Select the activity on the critical path with the lowest cost slope and decrease its duration by one day.

3. Enter the resulting cost of compression on the Summary Table (Figure 4-14).

| Cycle | Activity Duration Reduced | Remaining Time in Activity to Crash | Cost | ES/LF Final Node | Σ Cost | Project Length |
|---|---|---|---|---|---|---|
| 1 | A | 0 | 10 | 15 | 10 | 14 |
| 2 | D | 0 | 20 | 14 | 30 | 13 |
| 3 | C | 1 | 40 | 13 | 70 | 12 |
| 4 | B | 1 | 50 | 12 | 120 | 11 |
| 5 | B | 0 | 50 | 11 | 170 | 10 |
| 6 | E & C | 1 & 0 | 60 | 10 | 230 | 9 |

Figure 4-14. Compression Summary Table

4. Determine the new critical path.

5. Repeat the process starting with step 2.

The procedure for this method is not detailed enough and may be unclear to someone that is not familiar with schedule compression. The method does not explain what steps to take when a second critical path develops because of crashing, nor does it explain how to determine when the project can no longer be compressed.

Willis Method

The Willis method of schedule compression is based on the arrow diagram and uses the following steps (10:306-317):

1. Draw the CPM diagram. Show the number of days that each activity can be crashed, the cost slope for each activity, and the total float of each activity.
2. Draw sections. The sections must pass through the diagram vertically. A section can pass through any activity except those that are critical but non-crashable. As the compression process is continued, additional activities will become critical, and the remaining crashability of some activities will be reduced.
3. Find the least-cost section. The least cost-section is the one in which the sum of the crash costs for the critical activities it passes through is the lowest. Tabulate section crash costs for each compression cycle(cut) on a table such as the one shown in Figure 4-15.
4. Crash all the critical activities on the least cost-section. The number of days that these activities can be crashed is the least of:

   a. The remaining crashability of any critical activity through which a section passes.

   b. The total float of any noncritical activity through which the section passes.

| Cut Number | Section | Cuts Critical Activities | Crash Cost, $ per Day Activity | Crash Cost, $ per Day Section | Crash Section, Days | Crash Cost for Section, $ |
|---|---|---|---|---|---|---|
| 1 | a-a | A | 90 | 90 | | |
| | b-b | C | 190 | 190 | | |
| | c-c | C | 190 | 190 | | |
| | d-d | G | 50 | 50 | 2 | 100 |
| | e-e | G | 50 | 50 | | |
| | f-f | I | 65 | 65 | | |

Figure 4-15. Tabulation of Section Crash Costs Before Cut

| Cut Number | Crash Activities | Activity Crash Cost per Day, $ | Total Crash Cost per Day, $ | Crash Project, Days | Revised Duration, Days | Cumulative Cost, $ |
|---|---|---|---|---|---|---|
| 0 | Prior to Crashing | | NA | NA | 50 | 0 |
| 1 | G | 50 | 50 | 2 | 48 | 100 |
| 2 | I | 65 | 65 | 2 | 46 | 230 |
| 3 | A | 90 | 90 | 2 | 44 | 410 |
| 4 | G<br>H | 50<br>30 | 80 | 2 | 42 | 570 |
| 5 | B<br>C | 140<br>190 | 330 | 2 | 40 | 1230 |
| 6 | C<br>D | 190<br>390 | 580 | 1 | 39 | 1810 |
| 7 | D<br>F<br>G | 390<br>290<br>50 | 730 | 1 | 38 | 2540 |

Figure 4-16. Tabulation of Compression Costs

Tabulate the results on a table such as that shown in Figure 4-16.

5. Reduce the crashability of crashed activities. Annotate the diagram with the remaining crashability of all crashed critical activities.
6. Reduce the total float of non-critical activities through which the section passes if the non-critical activity is concurrent with all crashed critical activities.
7. Reduce the total float of other non-critical activities. Reduce the total float of any other non-critical activity so that the lowest total float of any arrow originating at a node is equal to the lowest total float of any arrow terminating at the node.
8. Repeat the process as often as possible. Repeat steps 2 to 7 until the project duration can be reduced no further.

The use of vertical section lines drawn through the network is a technique that adds to the complexity of this method. In a large network, the section lines could add clutter and make the network hard to follow. The sections are used for deciding which activities to crash, checking for network limitations, and updating the network. These same tasks are accomplished with less confusion in the Antill/Woodhead method.

To illustrate schedule compression procedures in text-books, authors use example projects that generally have eight to fifteen activities. A project of this size is sufficient to illustrate the compression procedures, but is not realistic. Real construction projects can have hundreds of activities--almost requiring the use of scheduling software to solve network calculations efficiently.

With these realities in mind, it would be logical to choose a schedule compression method that is easy to understand and simple to use. The methods summarized earlier in this chapter that involve the use of many tables are not recommended because they can be even more difficult to understand and follow as the project size increases. Methods that involve complex calculations to figure out which activities to crash and to update networks are also not recommended.

The Herbsman method and the Antill/Woodhead method are recommended for any size of project. They are both easy to understand and simple to follow. There is a trade-off between the two methods--the Herbsman method involves more crash cycles because each cycle reduces the project by one day, while the Antill/Woodhead method involves more network analysis during each cycle to find network limits. Because of this trade-off, both of these methods are equally recommended, although each compression cycle is a little easier with the Herbsman method.

With any method selected, schedule compression can be a very time consuming undertaking, especially with a large project. Determining normal and crash durations and costs for each activity can be an expensive and lengthy procedure. For this reason, only relatively few activities are often chosen as crash candidates--based on their potential for time savings. This decision is usually based on the project manager's experience.

# CHAPTER FIVE

## CONCLUSION

The importance of time in the construction project can not be overstated. To the owner, the sooner the project is complete, the sooner operation and use of the finished project can commence. Economically, time equates to thousands of dollars per day, depending on the project's ultimate use. Considering these stakes, it is of vital interest to the owner to shorten the entire project delivery time, from the determination of the need for the new facility to the turnover of the completed project. Each day of delay can result in unacceptable losses in revenue or additional expenses.

Time is also of great importance to the contractor during the construction of the project. Indirect and overhead costs continue to add up while construction is underway. Delays in final completion can result in an erosion of profits, or even losses.

As discussed previously, there are numerous ways to compress the time needed for project execution and completion. Efforts on the part of all parties involved throughout each phase of the construction process were presented. All techniques discussed may not be applicable in every situation or on every project, but it is up to the owner, the architect/engineer, and the contractor to apply these

techniques as applicable to achieve the goal of delivering the project at the economically optimal time.

The determination of the least cost construction schedule can maximize a contractor's profit. A methodology has been presented to find the minimum cost schedule--with a variety of compression procedures to determine the time versus direct cost curve. All of the methods will lead to the same time-cost curve. Since schedule compression can be a time consuming task, a method should be selected that is easiest to use and follow. This report has recommended two of eight methods studied, based on their simplicity, understandability, and applicability to projects of all sizes.

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